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Influence of Sediment on the Hydrological Performance of a Permeable Pavement

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Abstract

Permeable pavements play an essential role in urban drainage systems, making them a subject of great interest to both researchers and practitioners. The majority of studies, however, have demonstrated a significant degree of uncertainty regarding both the operational performance and maintenance requirements of this type of pavement. This paper describes a laboratory-based experimental study investigating the influence of sediment on the hydrological performance of a permeable pavement. The experimental results show that, under sediment and rainfall loading typical for a 10 year period within the UK, the partial clogging of the pavement voids with sediment led to a 6.4% decrease in total outflow, a 6.41% decrease in outflow rate, a 9.5% increase in outflow start time, a 20.7% increase in total outflow duration and no significant change in suspended solid concentration. However, no surface ponding was observed and it was therefore concluded that an appropriately designed permeable pavement system, exposed to typical UK rainfall and sediment loadings, should be able to operate efficiently for at least 10 years without the need for any post-construction maintenance. Hence, permeable pavements continue to represent an excellent form of source control for both surface run-off and pollutants.

Keywords

Permeable pavement; hydrological performance; sediment; suspended solids; outflow; SuDS

1 Introduction

Permeable pavements are a key Sustainable Drainage System (SuDS) measure to attenuate surface runoff in urban areas (Pratt et al., 1989; USEPA, 1999; Schluter, 2002; Dawson, 2009). They can also be used to filter out some of the pollutants that commonly occur in urban runoff (Hatt et al., 2007; Siriwardene et al., 2007; Beecham et al., 2012).

The effective life of a permeable pavement can be defined as the period of time the pavement remains in service before the rate of infiltration is reduced to an unacceptable level (Yong et al., 2013). This lifespan is primarily governed by the permeability of the materials employed, which decreases with the accumulation of sediment within the pavement structure. This accumulation process is thought to be particularly significant during the first few years in service (Borgwardt, 2006; Dierkes et al., 2002). Although manufacturers' data indicate that a permeable pavement should remain serviceable for 20 to 25 years (Wright et al., 2010; Pezzaniti et al., 2009), there remains significant uncertainty regarding the influence of sediment on a pavement's operational performance and maintenance requirements (Abbott and Comino-Mateos, 2003; Newman et al., 2013).

This paper helps address current uncertainty by presenting the findings from a comprehensive experimental programme to assess the influence of sediment on the hydrological performance of a permeable pavement.

2 Experimental Methodology

2.1 Experimental apparatus

As shown in Figure 1, the experimental apparatus consisted of a section of permeable pavement, a water delivery system and a data acquisition system. Full details of the experimental apparatus can be found elsewhere (Alsubih et al. 2016), whilst a brief overview is given below.

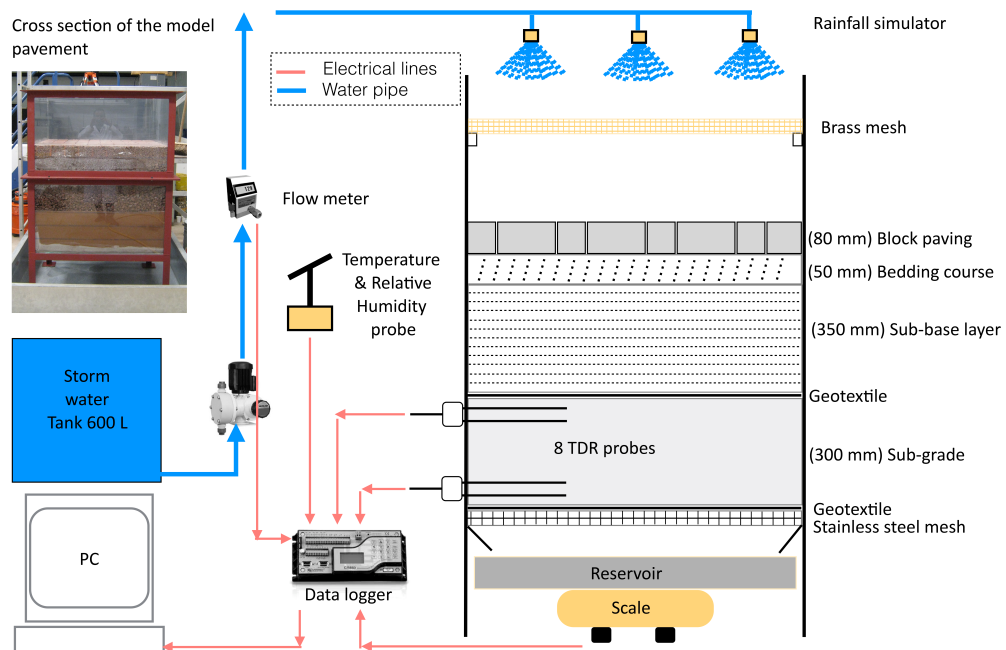


Figure 1: Layout of the permeable pavement and associated equipment.

The permeable pavement was designed to represent a car park surface at full-scale, and its' construction was based on technical guidelines provided by the SuDS Manual CIRIA C753 (Woods-Ballard et al., 2015) and the relevant British Standard 7533-13:2009 (BSI,

2009). The pavement had an overall depth of 780 mm, comprising of a 300 mm sub-grade layer, a 350 mm sub-base, a 50 mm laying course and a 80 mm block paving.

The water delivery system was designed to control rainfall volume, intensity and duration. Water was pumped through stainless steel spray nozzles and discharged onto a brass mesh (placed above the pavement) to induce drops more representative of those found during actual rainfall.

The data acquisition system consisted of a flow meter to measure inflow rate, a weighing scale below the pavement structure to monitor outflow rate, humidity/temperature sensors and time domain reflectometry probes located within the sub-grade to monitor pavement Volumetric Water Content (VWC). To ensure representative moisture content data, four probes were placed in both the top sub-grade layer (75 mm from the surface) and the lower sub-grade layer (225 mm from the surface). In addition to this automated data collection, outflow samples were manually collected during rainfall events to measure Suspended Solid Concentration (SSC).

2.2 Experimental procedure

As the purpose of the study was to determine pavement performance over an extended period, and time constraints prohibited a “real-time” experimental programme, it was necessary to use an accelerated testing regime. After careful consideration of the various logistical constraints (including a ban on laboratory testing over weekends and December shutdown), a testing programme of 120 rainfall events over an equivalent period of 24 weeks (a total of 189 days achieved in two testing periods intersected by a 21 day dry period due to December laboratory shut down) was developed (one event per weekday and no events on weekends). With each event having a constant intensity of

25.56 mm per hour and lasting 2 hours and 45 minutes, the 120 rainfall events equated to the average precipitation in Edinburgh for a period of 12 years; hence the testing programme can be considered to represent 12-simulated years of rainfall, comprised of:

- The initial day counted as the first day of the experiment period (Phase 1);
- First 2-simulated years before adding sediment (Phase 2); and
- 10-simulated years since the start of sediment addition (Phase 3).

Although not testing at the weekend would allow the pavement to partially dry out, the drying process was found to be very slow (see section 3.1), and it is therefore acknowledged that the pavement VWC would be greater than zero and not necessarily identical at the start of each testing cycle (i.e. at the start of each week). Whilst this was an unavoidable consequence of time and logistical constraints, it is important to note that the experimental programme was primarily intended to investigate the long term impact of sediment on the hydrological performance of a permeable pavement, rather than the secondary impact of antecedent conditions. While it is acknowledged that the influence of wind and solar radiation is important on permeable pavement function, neither have been explicitly included in this laboratory experiment due to the focus on sediment impact on infiltration capacity.

During the first 2-simulated years of testing, no sediment was added to the pavement so as to allow any internal sediment to wash out from the rig prior to the introduction of the test sediment. This helped ensure that the sediment data collected was solely due to the deliberate application of the known quantity of sediment.

Sediment, equivalent to 440 kg/ha/year (Ellis, 1996), which represents average sediment loading for car parking area in UK, was applied manually (with a sieve) to the pavement surface prior to each cycle of rain events after the first 2-simulated years. The material

selected to simulate natural sediment was sand (d₅₀ of 250µm), which was clean from organic matter to prevent biological activity within the pavement rig. Clearly the use of a single sediment type and size is not necessarily representative of the full range of sediment loads that a real-world pavement would be exposed to, but given the general uncertainties surrounding the impact of sediment in pavement performance, it was considered that a more complex approach would unnecessarily complicate analysis of the experimental findings.

3 Results and Discussion

The results from the experimental programme are detailed below, and include a brief overview of the testing undertaken prior to the sediment testing programme, as this gives a valuable insight into the basic performance of the pavement structure.

3.1 Previous experimental results

Prior to the sediment experimental programme, the pavement was exposed to a series of rainfall events (with no added sediment) between September and December 2012, to study hydrological performance (Alsubih, et al, 2016). As would be expected, the VWC increased throughout this initial testing, and the sub-grade was fully saturated at its conclusion (VWC was 18.4% and 18.9% for the top and bottom sub-grade layers respectively). It is noted that the VWC for the upper layer of sub-base (VMC top-layer, Figure 2) is consistently lower than the bottom layer. It is suggested that this occurs due to the infiltration rate of the sub-base material being greater than the rainfall intensity, thus allowing greater conveyance and resulting saturation in the lower depths of the sub-base layer.

Following the initial hydrological experiments, the pavement was left to dry out during the first 7 months of 2013 (1st dry period). As shown in Figure 2 (phase 2), this resulted in deep evaporation and infiltration and a consequent 51.4% drop in VWC. This dry period was followed by a short series of rainfall-only tests which resulted in a distinct increase in VWC, and a further dry period (2nd dry period, phase 4, Figure 2) which resulted in a VWC drop similar to that observed during the initial phase of the 1st dry period. In common with other testing phases, the decrease in VWC was less pronounced with depth below the pavement surface.

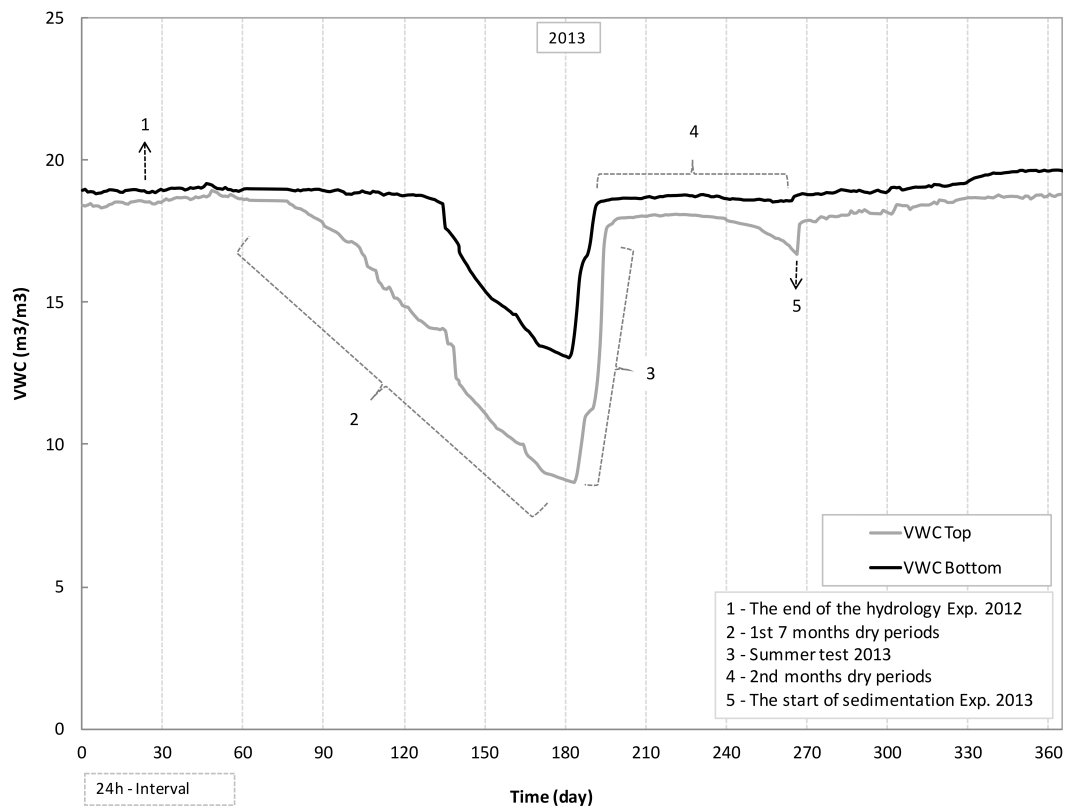


Figure 2: Showing volumetric water content (VWC) throughout 2013.

The drying process was found to be very slow and primarily dependent on laboratory atmospheric conditions. The laboratory temperature changed very slowly over time (maximum and minimum temperature were 26.8°C and 19.1°C , with average

temperature was 23.4 °C), and remained relatively constant compared to the outdoor temperature fluctuations observed during 2013. The only notable difference in atmospheric conditions was relative humidity (RH) which increased from a relatively constant autumn-spring value (35.6% average) to ~50% during the summer months. The results and observations from these pre-sediment experiments indicate that the pavement may take months, potentially years, to become fully dry under laboratory conditions.

3.2 Sub-grade conditions

The sediment experimental programme ran between September 2013 and April 2014, with a three week dry period over the Christmas/New Year, when Health and Safety regulations again prevented testing. As shown in Figures 2 and 3a, the VWC varied throughout the testing period, most notably in the top layer of the sub-grade, but remained virtually constant during the three week dry period. The maximum and minimum temperature were 26.5°C and 19.3°C, with average temperature was 23.9 °C), indicating that the temperature was less variable for the course of the experiment. Relative humidity was notably varied at the beginning of the experiment (32.7% average), but remained relatively constant throughout the rest of the experimental period.

3.3 Outflow volume

3.3.1 The initial day

Prior to commencing sediment testing, the moisture content in the subgrade was 16.6% and 18.6% in the top and bottom layers respectively, and the initial condition of the sub-grade was clearly not 100% dry (see Phase 1 in Figure 3a). After the rainfall on the first

day, there was an increase of approximately 6.6% and 0.8% in VWC in the top and bottom subgrade layers respectively.

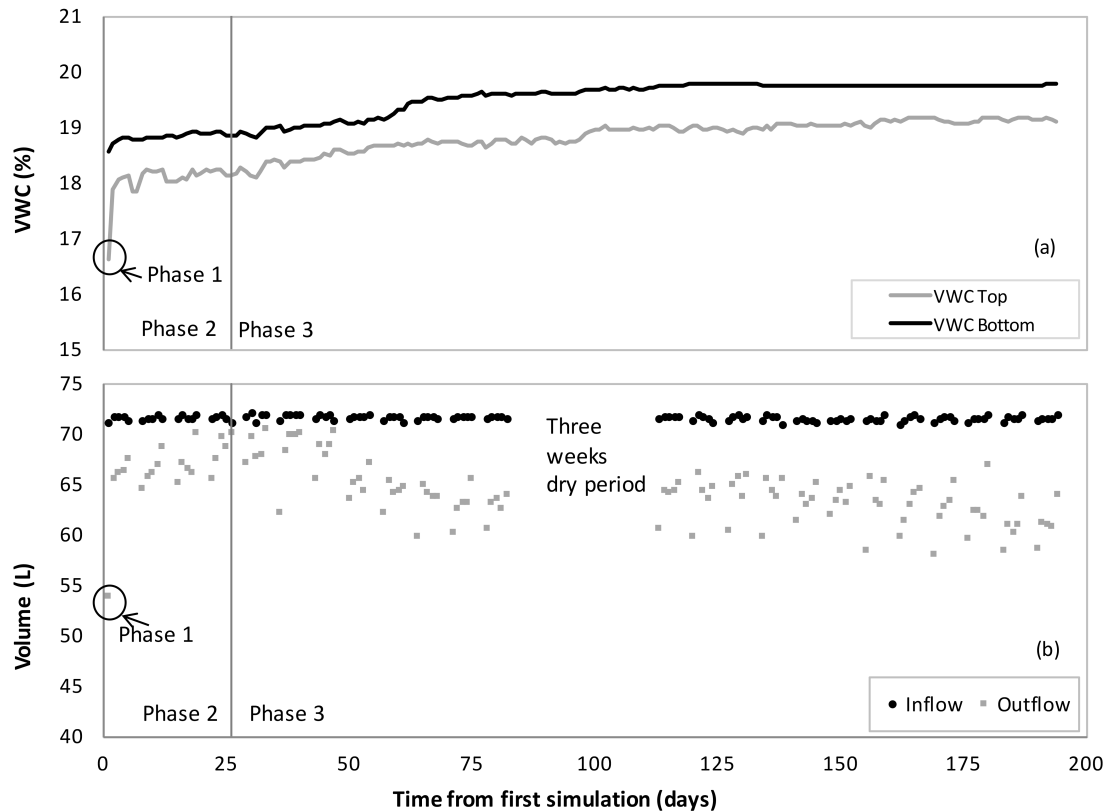


Figure 3: Showing (a) the VWC over the course of experiment, (b) outflow and inflow volume over 120 rain events, including phase 1 (initial day), phase 2 (pre-sediment) and phase 3 (post-sediment).

3.3.2 Pre-sediment addition

This experimental phase covers the pavement performance during the first 2-simulated years (phase 2, Figure 3). As shown, this period was characterised by a general increase in both VWC (Figure 3a) and outflow (Figure 3b) with time. As the bottom layer was already saturated, the increase in its VWC (0.76%) was less pronounced than that in

the lower layer (2.12%), whose conditions visibly varied during each event until the pavement sub-layers reached saturation equilibrium.

It is possible to compare the pre-sediment and initial phase. The bottom layer had almost the same percentage change in VWC value within the two phases, 0.76% and 0.80% for the initial and pre-sediment phase respectively. This indicates that the change in VWC was very gradual during the pre-sediment phase and that the bottom layer of the sub-grade reached saturation earlier. The top layer VWC increased by 2.12% within the pre-sediment phase, compared with 6.6% during the initial phase, indicating that the change in VWC was very slow. However, it can be seen that the pavement reached the saturated condition during the pre-sediment phase.

3.3.3 Post-sediment

Figure 3a (Phase 3) shows the VWC during the post-sediment phase. The increase in VWC was 5.69% and 4.84% for the top and bottom layers respectively for the period of post-sediment monitoring. Although the top layer consistently shows a greater increase, due to its dryer initial condition, it is clear that the percentage increase was approximately equal for both layers. Both layers reached the same saturated condition relative to their starting conditions.

The relationship between the outflow volume and the VWC shows highly significant ($p > 0.01$) moderate correlation. It is positive correlation between outflow and VWC before addition of sediment ($r = 0.651$ and 0.656 for top and bottom layer, respectively). Conversely, the relation becomes negative after the addition of sediment ($r = -0.561$ and -0.512 for the top and bottom layer, respectively). The change in the type of relationship can be explained as being attributed to the addition of sediment

3.4 Start delay and outflow duration

Start delay is defined as the time taken (since rainfall initiation) for outflow to occur at the base of the pavement. As shown in Figure 4a, the longest start delay (23 minutes, 14% of total outflow duration) occurred with the very first test. After this initial, prolonged delay, it can be seen from Figure 4a that the start delay ranged between 5.5 and 10.5 minutes with an average of 7.67 minutes (SD 1.02mins), corresponding to 9.5% of the total outflow duration.

This would indicate that the addition of sediment increased start delay.

Outflow duration is defined as the time (from initial outflow) for the outflow to reach 6.7×10^{-5} l/s. As shown in Figure 4b, there was a gradual increase in outflow duration during the 120-test experimental programme. After the addition of sediment, the outflow duration range increased to 5.9 - 16.18 hours with an average of 11.36 hours (SD 2.23h), which equates to a 20.7% increase relative to the pre-sediment data. This would indicate that the addition of sediment increased outflow duration.

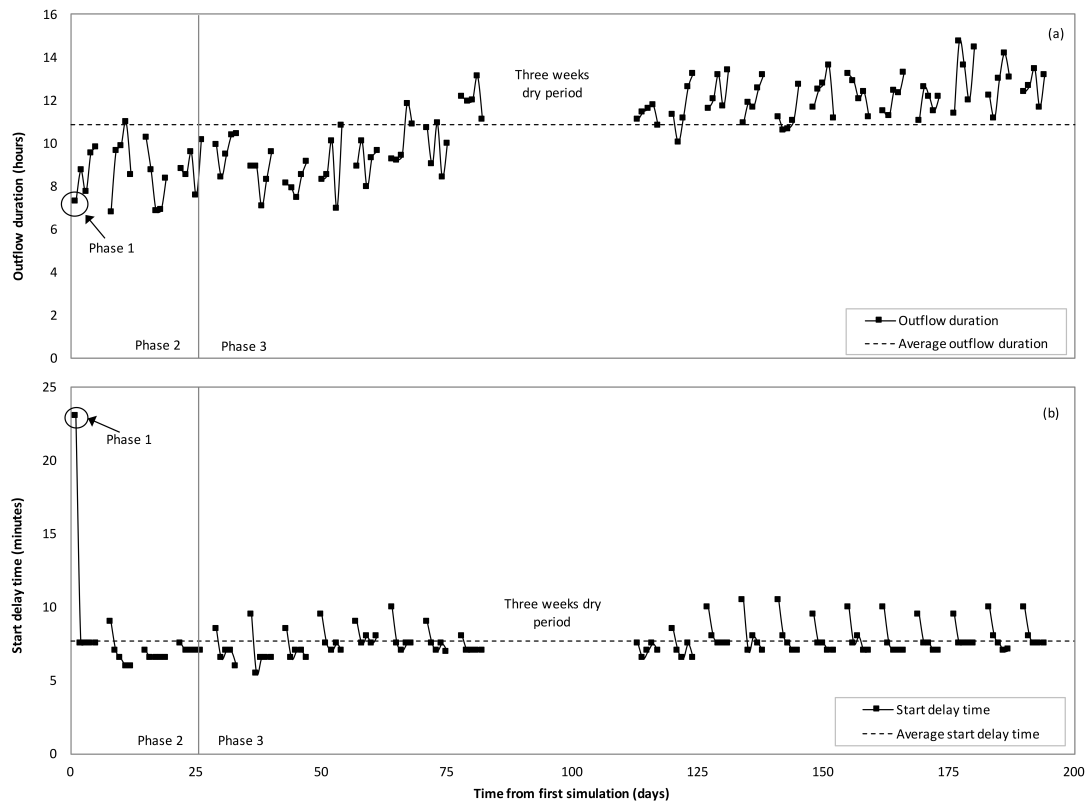


Figure 4: Showing (a) Start delay over the period of experiment; (b) Outflow duration over the period of experiment.

3.5 Outflow rate

Figures 5 illustrates how pavement outflow varied during the first 30 minutes of each of the 120 tests. The 10 curves in each figure correspond to the tests undertaken on days 1-5 and 8-12 of the testing cycle, with the 2 day “dry period” corresponding to the weekend. The loading for each testing cycle equates to one year real time, and hence each figure corresponds to 1-simulated year of sediment and/or rainfall loading.

It is apparent from the results of the first day of the first cycle (Figure 5) that the test rig was initially very dry, as outflow was only registered from ~23 minutes into the test. The remaining curves illustrate a definite pattern, with the outflow/time curves for the first two

days starting later and (generally) being less steep than those for the remaining 3 days; this clearly shows the impact of the weekend dry period, which allowed the pavement to partially dry out and increase its void capacity before further rainfall loading.

In addition to this inter-cycle variation, Figure 5 also shows more subtle variations in the outflow curves between individual cycles, particularly after the addition of sediment in the 4th-simulated year (Figure 5). From this point onwards, the outflow rates started to decrease, clearly showing the impact of the accumulated sediment impact on water movement through the structure. In addition, the “banding” of the outflow curves (days 1-2 and days 3-5) also become more apparent, illustrating that the pavement was becoming increasingly saturated. Looking across all of the data, there was a 6.38% percent reduction in outflow over the 12-simulated year period.

3.6 Suspended solids

3.6.1 Pre-sediment addition

As shown in Figure 6, the average SSC during the first 2-simulated years (i.e. prior to addition of sediment) ranged between 5.0 - 21.4 mg/L (SD 19.21 and 2.77 respectively). These relatively high initial values were to be expected; although the material used to construct the test rig was pre-washed, the pavement structure “flushed out” any residual fine material occurring as a result of construction activities and settling of internal pavement material. Consequently, the results from the 2nd-simulated year (5 mg/L) were used as a baseline, with all other SSCs above this level being considered to be a direct result of the sediment load applied to the pavement surface. It should be noted however, that it is likely that some internal discharge continued over the experiment period.

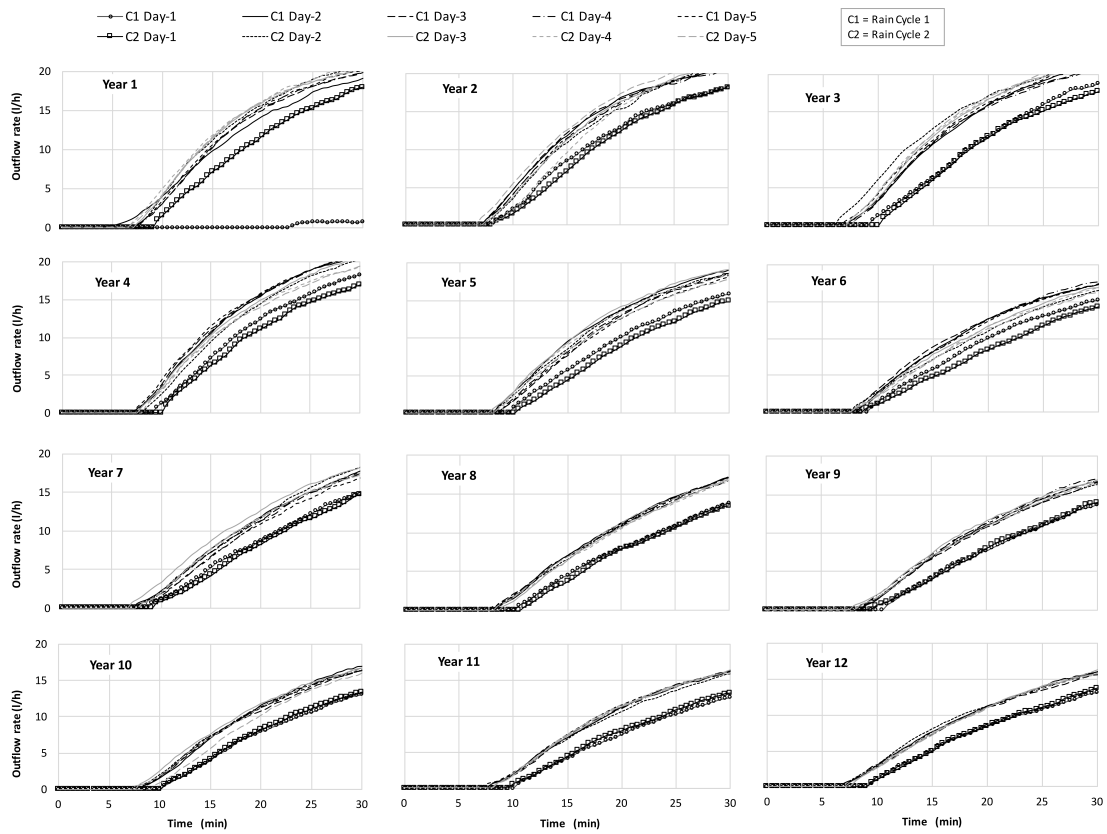


Figure 5: Graphs showing the outflow rate over 12-year simulations including 120 curves.

3.6.2 Post-sediment addition

The addition of sediment began in the 3rd-simulated year of testing, and the average SSC the over the next 9-simulated years ranged between 4.07 - 10.19 mg/L. Figure 6 illustrates that the pattern of sediment discharge throughout this period, with a general trend of decreasing SSC with time.

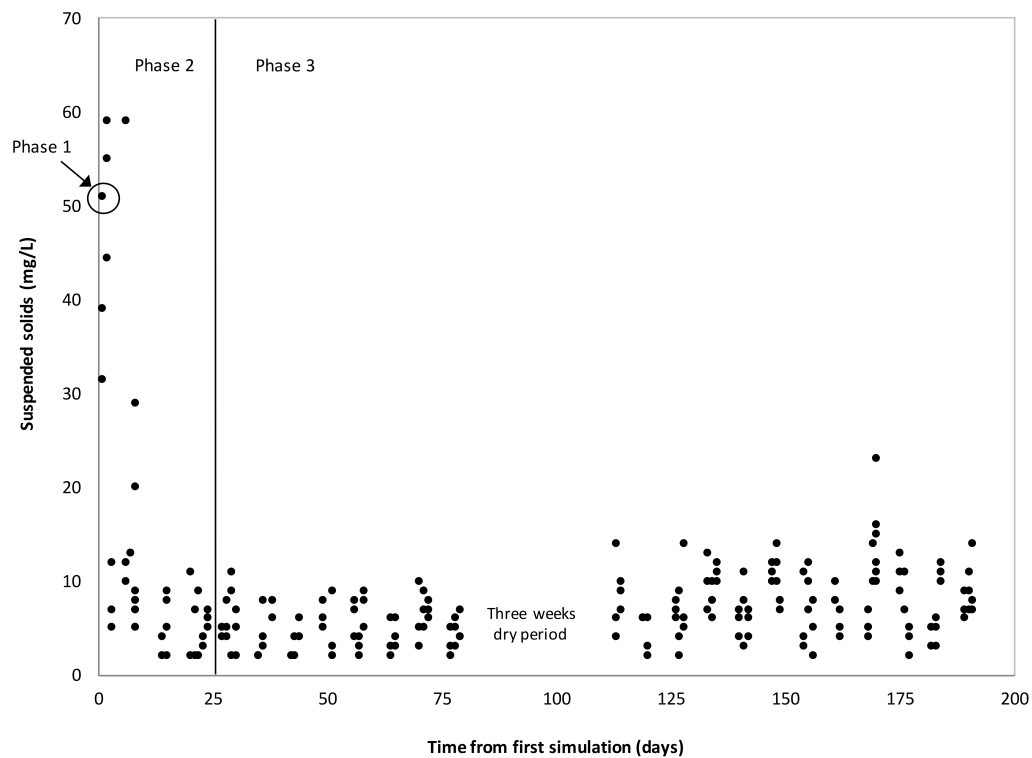


Figure 6: Average concentration of suspended solids over a 24-week period.

After the three week dry period (New Year break), the variability of the SSC increased, and it is difficult to identify whether this was due to continued sediment addition or the actual occurrence of the dry period. However, before the three week dry period there was no obvious variation in comparison to after the break. The variation that occurred after break was therefore attributed to the dry period.

Further analysis was carried out to verify whether there was a difference in SS concentration between each year of rainfall simulation. A paired t-test was carried out for comparison between the second year and all other simulated rainfall years, in order to identify the change in SS level over the experimental period. The results from the 2nd year of simulation were used as a baseline and all sediment results above this level (5mg/L) were considered to result from the additional sediment load on the pavement

surface. The results from the paired t-test Table 1 indicate that there is a t-test value difference after the seventh year of simulation. This confirmed that the slight change in SS concentration level occurred due to the three weeks dry period between simulated rainfall years six and seven.

Table 1: Paired t-test for comparison of different SS concentration. Critical t is 1.79(p=0.05)

Year simulation	Average SS concentration (mg/L)	t-test	Significantly* different from Year 2
1	21.41	4.13	Yes
2	5.00	-	-
3 ^a	5.24	0.70	No
4	4.07	0.74	No
5	4.93	0.34	No
6	5.50	0.96	No
7 ^b	7.42	1.84	Yes
8	8.22	2.33	Yes
9	8.23	1.95	Yes
10	6.93	1.80	Yes
11	10.19	3.70	Yes
12	7.76	2.00	Yes

*Significant when it is greater than 10% change from the year 2 value

^aThe Start of sediment addition

^bThree weeks dry periods occurred between 6 and 7-Year simulation

3.7 Conclusions

The experimental study detailed herein aimed to evaluate the performance of a permeable pavement under 10-simulated years of sediment loading. The detailed experimental findings highlight that addition of sediment resulted in:

- A 6.38% decrease in total outflow from the permeable pavement over the 10-simulated years.
- A 6.41% decrease in outflow rate from the permeable pavement over the 10-simulated years.
- A 9.5% increase in outflow start time from the permeable pavement over the 10-simulated years.
- A 20.7% increase in total outflow duration from the permeable pavement over the 10-simulated years.
- No significant change in the SSC within the outflow from the permeable pavement over the 10-simulated years (average SSC ranged 4.07 to 10.19 mg/l). However, whilst the variability of the SSC had a generally limited (low) variability during first 7-simulated years, there was significant difference in SSC after the 7th-simulated year, following three week dry period.

From the detail given above, the following key conclusions can be made:

- Addition of sediment leads to partial clogging of a permeable pavement structure, resulting in a decrease in infiltration rate and outflow volume, and an increase in outflow start time and duration.
- An appropriately designed permeable pavement system, exposed to typical UK rainfall and sediment loadings, should be able to infiltrate rainfall (without ponding) for at least 10 years without the need for any post-construction maintenance. It can therefore be concluded that the working life of a permeable pavement should easily exceed ten years without maintenance, and hence they continue to represent an excellent form of source control for both surface run-off and pollutants.

Whilst the experimental results were collected under controlled laboratory conditions, which can only approximate rather than precisely duplicate field conditions, they do provide a valid representation of the key processes that occur within permeable pavement structures, and hence they can be used to give an indicative understanding of the processes and functionality in other locations.

In terms of future work, the work reported herein is currently being used to help develop simple models to determine pavement discharge characteristics for given flow and sediment loading; once complete, this work will be the subject of a future publication. In a more general sense, the results, observations and conclusions from the work reported herein point to two specific avenues; namely, experimental work to better understand how sediment characteristics (type, size, etc) influence performance and experimental/numerical work to better understand how antecedent conditions (particularly prolonged dry periods) affect long-term pavement performance

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